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## CONCISE METHODS FOR PREDICTING THE EFFECTS OF UNDERWATER EXPLOSIONS ON MARINE LIFE

BY GEORGE A. YOUNG  
RESEARCH AND TECHNOLOGY DEPARTMENT

1 JULY 1991

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## FOREWORD

The U.S. Navy has conducted a comprehensive program of research on the environmental effects of underwater explosion testing since 1970. This work has been documented in a series of technical reports and lectures. However, there is a need for brief, less technical, publications that can be distributed to regulatory agencies and the general public to clarify certain issues prior to the conduct of tests. As the physical effects of explosions on marine life usually receive more scrutiny and discussion than any other potential environmental effect, this topic has been given priority and is the subject of this report. It is expected that other topics will be treated in subsequent publications.

This report was prepared as part of the Ordnance Reclamation Project of the Naval Sea Systems Command (SEA 06R) under Program Element 63721N, Work Unit—Environmental Effects of Explosive Testing. This report is one of a series published under this sponsorship.

Approved by:



WILLIAM H. BOHLI, Head  
Energetic Materials Division

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## RESEARCH ON THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS BY THE U.S. NAVY

Experiments on the effects of explosions on marine life have been conducted since the 1940s by various organizations, but no satisfactory theory was developed to explain the results until the Navy initiated a systematic research program in 1970. The program has the following objectives:

- to conduct experiments on the effects of explosions on fish,
- to collect useful data from all possible sources,
- to develop prediction models based on sound theoretical concepts for injury to marine life,
- to investigate the deposit of explosion products in the atmosphere and marine environment,
- to develop prediction models for concentration levels based on explosion and dispersion theory,
- to develop methods to avoid or minimize all adverse environmental impacts,
- to investigate safe methods to cause marine life to temporarily leave a test site, and
- to provide technical support for compliance with relevant environmental laws.

This report is limited to the effects of explosions on common forms of marine life and on human swimmers.

Research was conducted in collaboration with fishery biologists at the Chesapeake Biological Laboratory in Solomons, Maryland. This partnership has been maintained to the present, and the body of accumulated knowledge has been a basis for consultation and involvement with almost all forms of underwater explosive work, including blasting, demolition, and channel clearance. Project personnel participated in tests against young salmon conducted in Alaska by the Oil and Gas Industry and worked with Minerals Management Service and National Marine Fisheries Service personnel on problems related to the explosive removal of offshore drilling platforms in the Gulf of Mexico. They also provided technical input at the Southwest Fisheries Center Seal-Bomb Workshop held in La Jolla in 1989.

During the early stages of research, emphasis was placed on studies of the effects of explosions on fish because of their dominant presence in the marine environment and their considerable economic importance. During later stages, special attention was given to marine mammals and sea turtles, which are present at some test locations. These species require maximum protection. Effects on swimmers were studied in other programs related to the safety of Navy divers, and the results are used here.

## COMMENTS ON SCALING OF UNDERWATER EXPLOSION EFFECTS

In many Navy experiments with underwater explosions, the charge weight is much less than the weight of an actual warhead. The data acquired on these tests can be scaled up in order to make predictions for military applications. The use of small-scale charges reduces costs and also limits the magnitude and extent of environmental effects.

In some experiments, scaling procedures become complex, but it is important to remember that doubling the weight of an explosive charge does not double the effects. Phenomena at a distance, such as the direct shock wave,\* scale according to the cube root of the charge weight. For example, if the peak pressure in the underwater shock wave from a 1-pound explosion is 1000 pounds per square inch at a distance of 15 feet, it is necessary to increase the charge weight to approximately 8 pounds in order to double the peak pressure at the same distance. (The cube root of eight is two.)

Effects on marine life are usually caused by the shock wave. At close-in distances, cube root scaling is generally valid. For example, the range at which lobsters have 90 percent survivability is 86 feet from a 100-pound charge and double that range (172 feet) from an 800-pound charge.

However, when this wave travels some distance through the water, it reflects repeatedly from the surface and seabed. It loses energy and soon becomes a relatively weak pressure pulse. At distances of a few miles, it resembles a brief acoustic signal. Therefore, shock wave effects at a distance may not follow simple cube root scaling but may decline at a faster rate. For example, the survival of swimbladder fish does not obey cube root scaling because it depends on the interaction of both the direct and reflected shock waves. In some cases, cube root scaling may be used to provide an upper limit in the absence of data for a specific effect.

## GENERAL NATURE OF ENVIRONMENTAL PREDICTIONS

Environmental predictions have much in common, whether they are made for estimating the effects of industrial air or water pollution, the effects of factory smoke on exposed personnel, the effects of automobile emissions on public health, the effects of noise on farm animals, and/or the damaging effects of oil spills, etc. All such predictions are statistical in nature because of the natural variability of ambient conditions, such as wind, weather, ocean currents, and atmospheric turbulence; in addition to the normal movements of people, wildlife, and marine life; and the range in size, age, and physical condition of all living organisms.

As a consequence of these factors, environmental predictions are not expected to be precise when applied to a single event. A single test may produce results that are above or below the predicted average. On the other hand, if a number of similar events occur, the average results should be consistent with predictions.

\*A steep-fronted compression wave generated in the water at the explosive boundary.

Since there is always a paucity of data for extreme conditions, such as very low dosages, low level physical effects, or natural events that rarely occur, predictions for low levels of probability are made by extrapolating data in the mid-range of probability.

When predictions of the environmental effects of underwater explosion tests are made, statistical methods are used for calculating the probability of injury of common species of fish with and without swimbladders. A different approach is followed for endangered species, sea mammals, sea turtles, and human swimmers. As no injury is acceptable in these cases, the calculated safe range is based on data from land mammals that indicate levels of effects that are not injurious.

In the complete absence of data, relevant information and physical and biological concepts are used and a "worst case" analysis may be employed.

For convenience, the various forms of life encountered in coastal waters (generally within 12 nautical miles of land) have been divided into four categories of vulnerability, starting with those that are the least vulnerable. These are listed in Table 1.

Figures 1 through 7 include typical calculated ranges for the four categories of vulnerability in addition to sample contours for swimbladder fish, porpoises, and swimmers. When contours are available, the extreme range is used for planning. The equations used for range predictions are summarized in Table 2. In most cases, the original predictions were made with computer programs based on complex physical-biological models. The equations presented here summarize the results in a concise form for use in the initial stages of planning.

## DEFINITIONS USED FOR TEST PLANNING AT SEA

### MINIMUM AIRCRAFT SURVEY RANGE

This is the range at which spotter aircraft fly for a period of at least one hour prior to a test. If swimmers, sea mammals, or sea turtles are observed within this region, or approaching it, tests will be delayed until they have left. The range is based on safety of human swimmers, as this exceeds the safe distance for marine life.

### MINIMUM SURFACE SURVEY ZONE

This is the close-in region that can be surveyed by personnel on shipboard, both visually and with fish-finders. It is usually based on the 90 percent survival of swimbladder fish weighing one pound or more. A small number of fish common to the area is acceptable. If a school of fish enters this zone, tests will be delayed until it leaves.

## SUMMARY

The information presented in this report is designed for preliminary planning only. Although the equations and discussions are technically correct, they do not cover all possible experimental conditions or marine environments. Before test plans are finalized for a particular site, it is always necessary to analyze the possible environmental effects in detail in order to provide a sound basis for developing mitigation measures and making other relevant decisions.

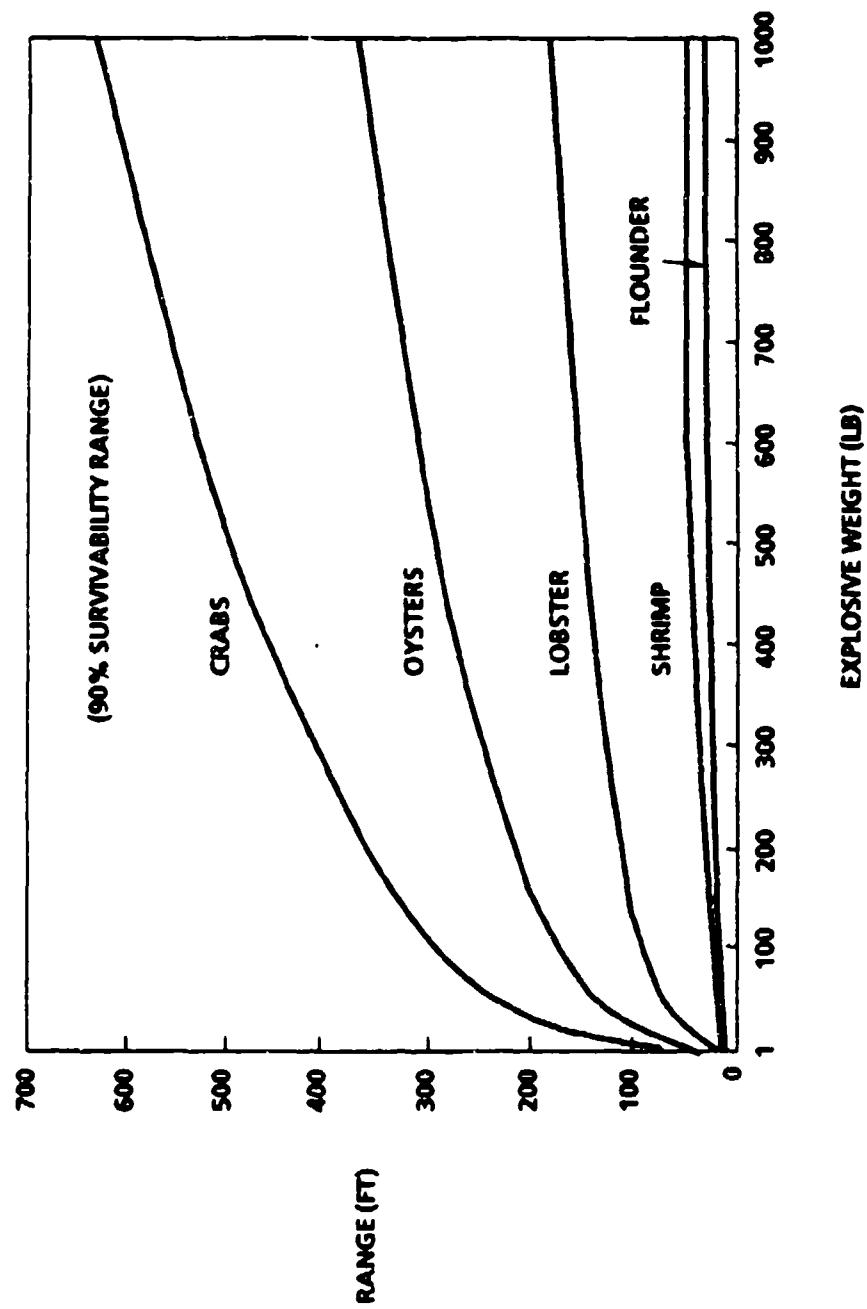


FIGURE 1. CATEGORY I: NON-SWIMBLADDER MARINE LIFE

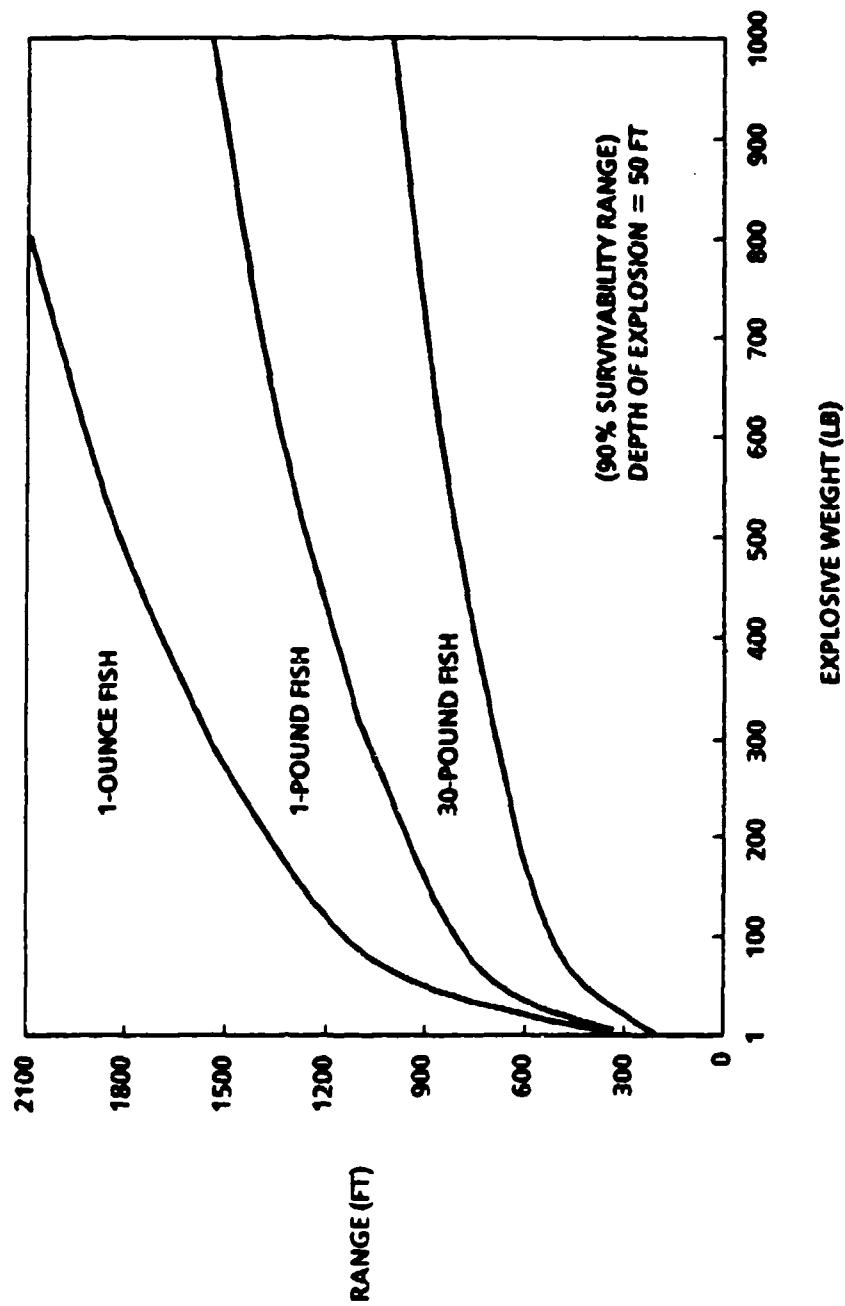


FIGURE 2. CATEGORY II: FISH WITH SWIMBLADDERS

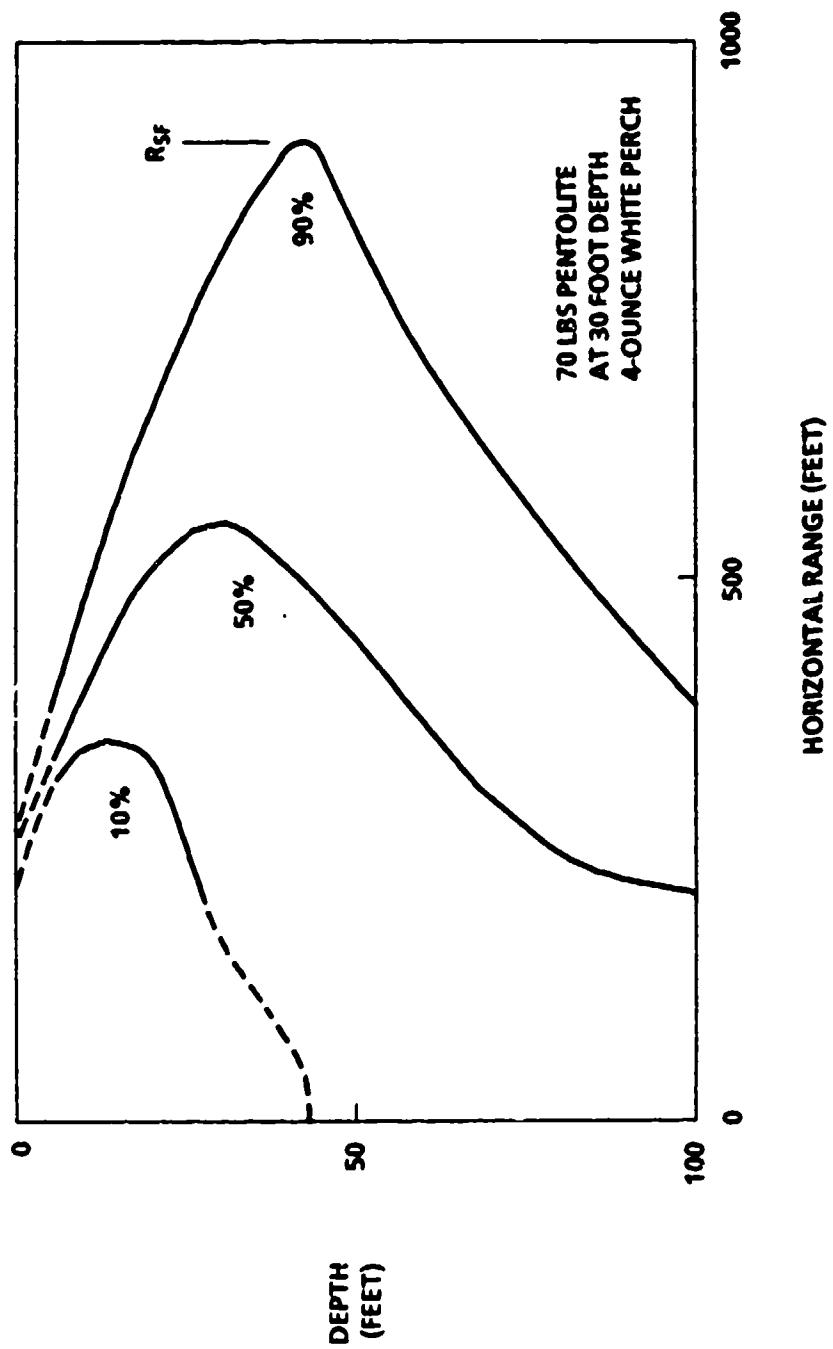


FIGURE 3. CONTOURS FOR SURVIVABILITY OF SWIMBLADDER FISH

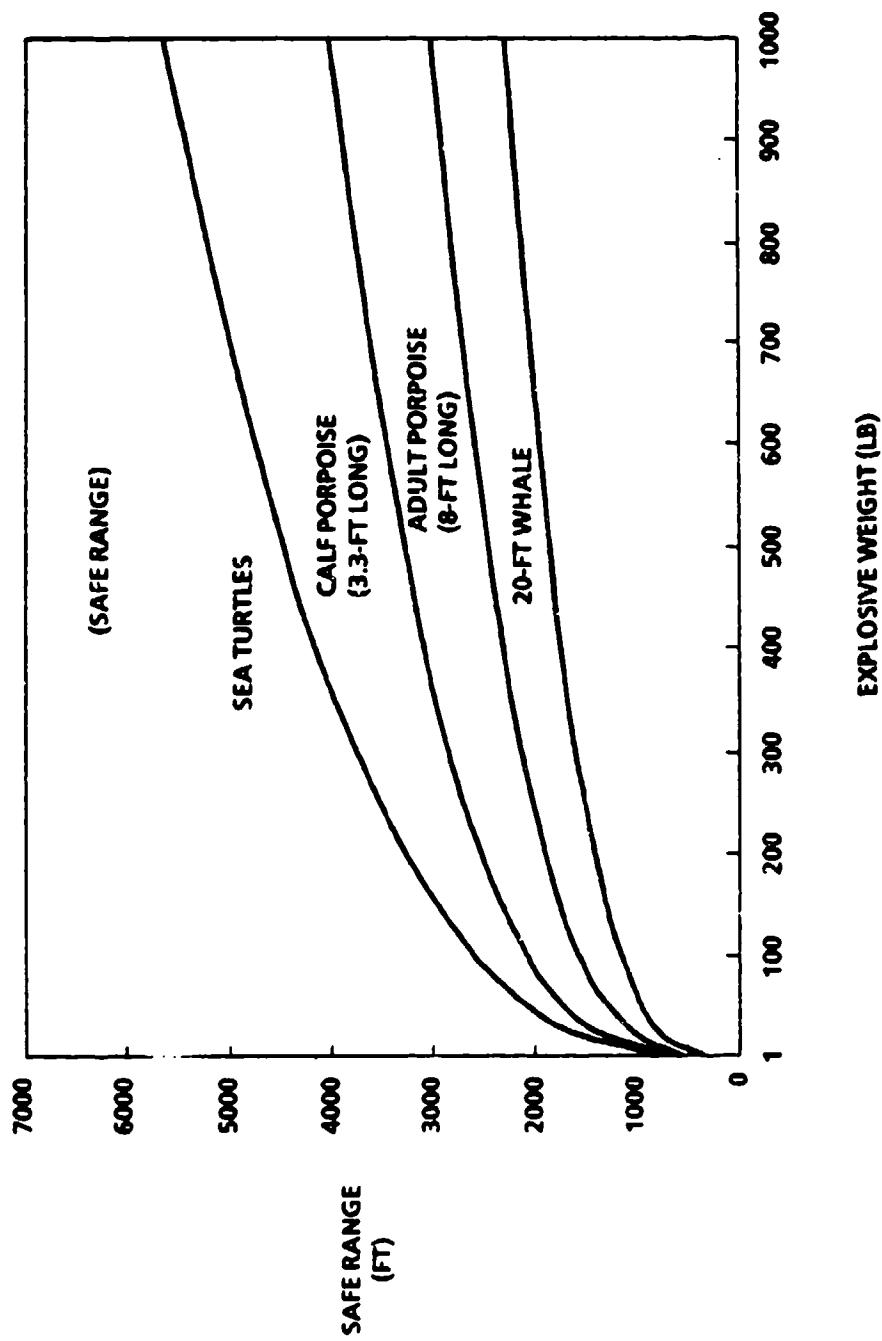


FIGURE 4. CATEGORY III: SEA MAMMALS AND SEA TURTLES

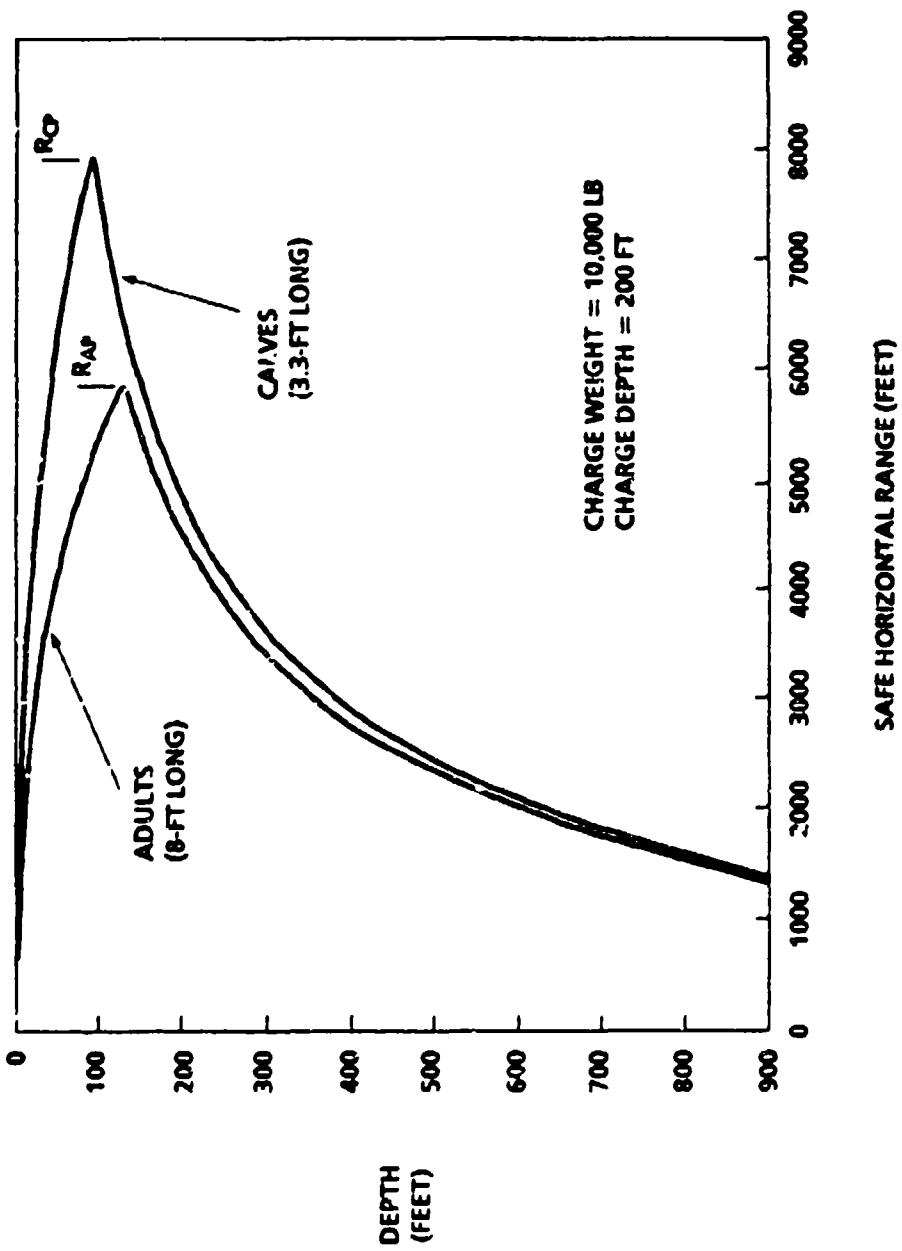


FIGURE 5. CONTOURS FOR SAFE RANGES FOR PORPOISES

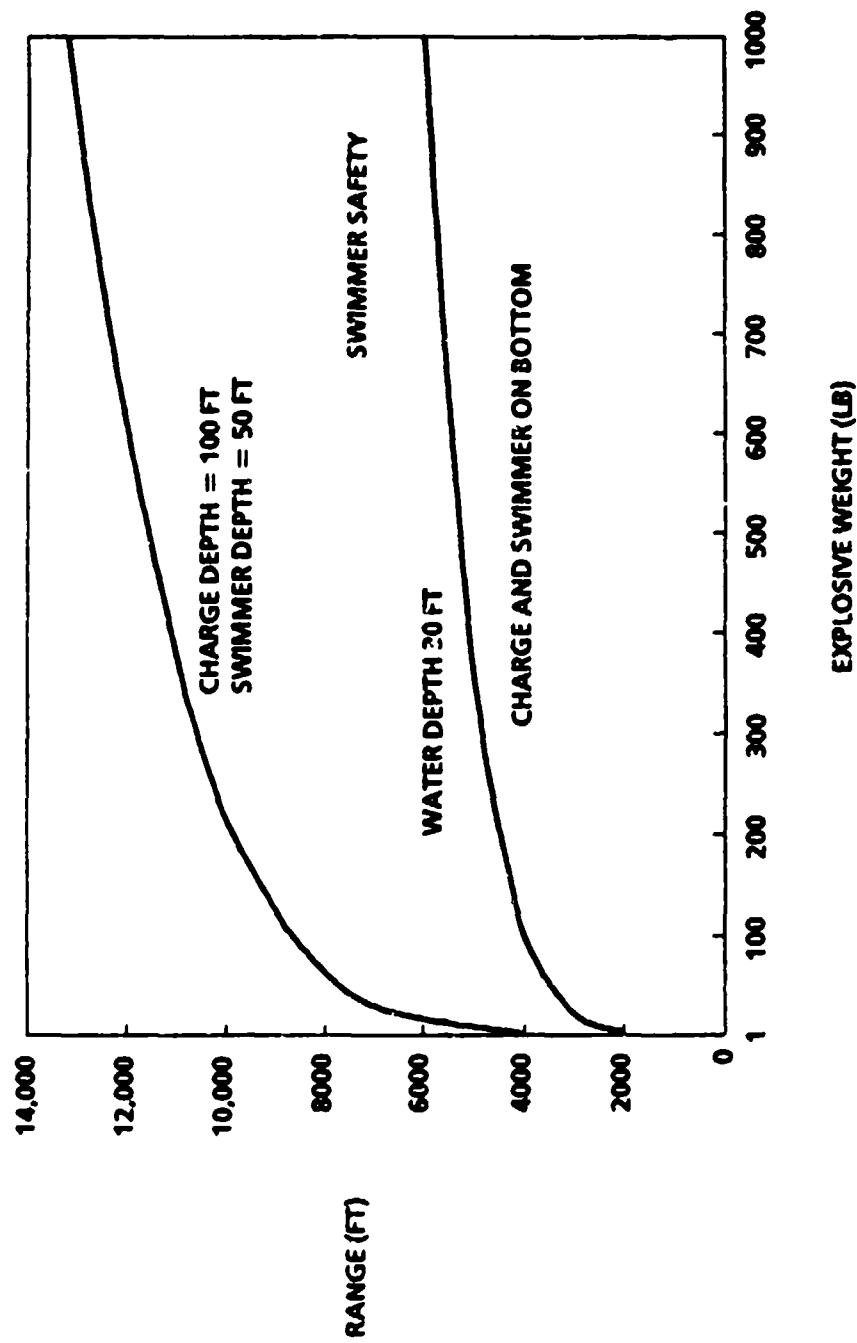


FIGURE 6. CATEGORY IV: SWIMMERS

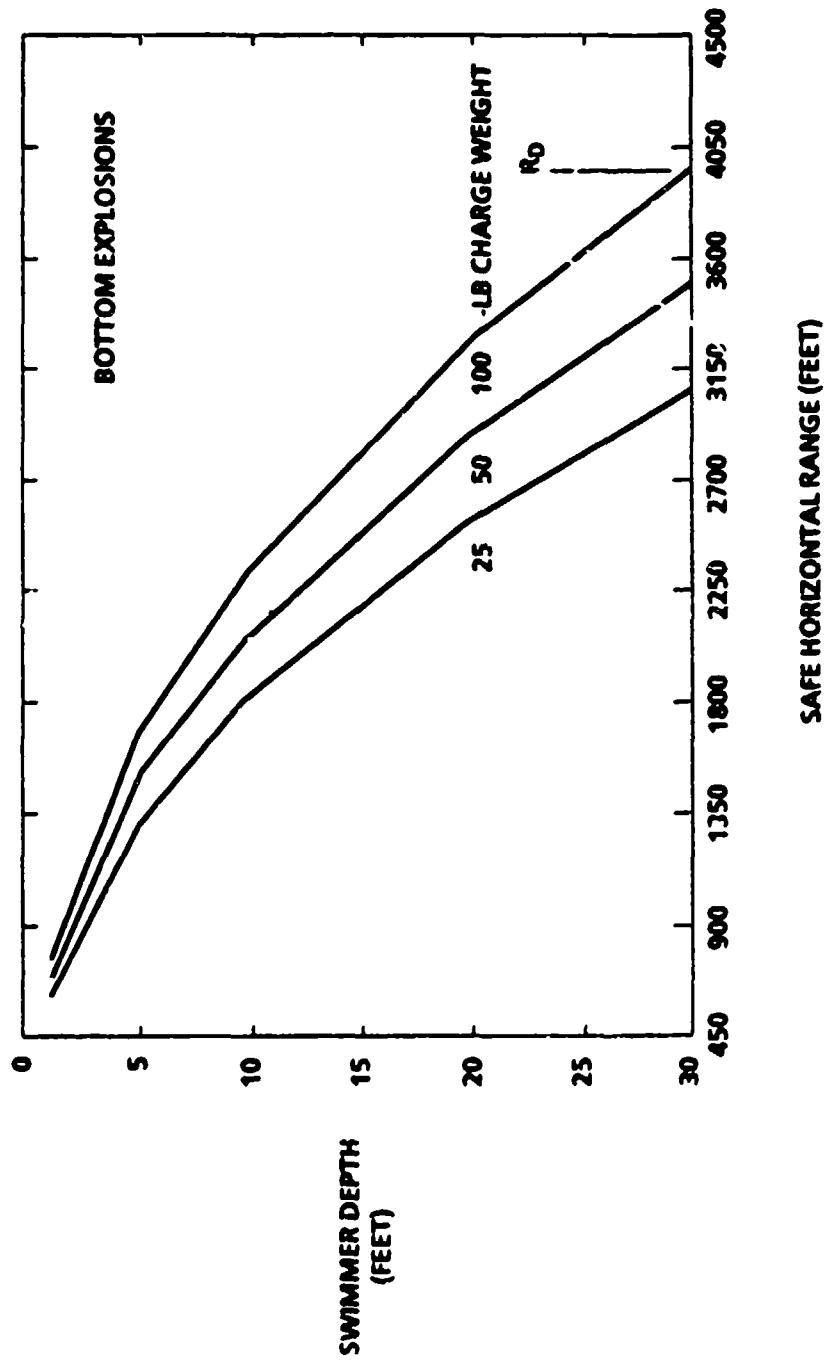


FIGURE 7. CONTOURS FOR SAFE RANGES FOR SWIMMERS IN SHALLOW WATER

TABLE 1. VULNERABILITY CATEGORIES

## CATEGORY I     NON-SWIMBLADDER MARINE LIFE

Flounder

Shrimp

Lobster

Oysters

Crabs

Comments: Highly resistant to explosions. Predictions are based on experimental data. Injury mechanisms vary with species, but resistance is probably due to the absence of air cavities. Estimated range of vulnerability based on 90 percent probability of survival.

## CATEGORY II     FISH WITH SWIMBLADDERS

Comments: Small fish are more vulnerable than large fish. Fish near the surface are more vulnerable than deep fish. Prediction models are based on experimental data and an injury mechanism related to the response of swimbladder gas to the direct and reflected shock waves. Estimated range of vulnerability based on 90 percent probability of survival at a relatively shallow depth.

## CATEGORY III     SEA MAMMALS AND SEA TURTLES

Comments: Small sea mammals are more vulnerable than large. Estimates of effects are based on experiments with land mammals. Injury is related to the response of air cavities, such as the lungs and bubbles in the intestines, to the shock wave. Estimated mammal safe range is based on absence of injury. Estimated safe range for sea turtles is based on Gulf of Mexico oil platform criteria established by the National Marine Fisheries Service. As a satisfactory biological-response theory has not been developed for sea turtles, cube-root scaling is used.

## CATEGORY IV     SWIMMERS

Comments: Safe ranges are determined by limited experimental data and a prediction model based on response of lungs and bubbles in the intestines to shock waves. Hazard to swimmers increases with water and swimmer depth. As the safe range for swimmers exceeds that for all forms of marine life, this range is used for aircraft surveillance of a test site.

TABLE 2. PREDICTION EQUATIONS

## CATEGORY I NON-SWIMBLADDER MARINE LIFE-90% SURVIVABILITY

Flounder	$R_{FL} = 3.38 W_E^{1/3}$
Shrimp	$R_S = 5.39 W_E^{1/3}$
Lobster	$R_L = 18.5 W_E^{1/3}$
Oysters	$R_O = 37.4 W_E^{1/3}$
Crabs	$R_C = 63.4 W_E^{1/3}$

## CATEGORY II FISH WITH SWIMBLADDERS-90% SURVIVABILITY

$$R_{SF} = 95 W_F^{-0.13} W_E^{0.28} (DOB)^{0.22}$$

## CATEGORY III SEA MAMMALS AND SEA TURTLES-SAFETY

Calf Porpoise, 200-ft DOB	$R_{CP} = 578 W_E^{0.28}$
Adult Porpoise, 200-ft DOB	$R_{AP} = 434 W_E^{0.28}$
20-ft Whale, 200-ft DOB	$R_W = 327 W_E^{0.28}$
Sea Turtles	$R_T = 560 W_E^{1/3}$

## CATEGORY IV SWIMMERS AND DIVERS-SAFETY

Swimmer and Charge on Bottom, 30-ft DOB	$R_D = 1730 W_E^{0.18}$
Swimmer Depth 50-ft, 100-ft DOB Deep Water	$R_D = 3800 W_E^{0.18}$

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R = Range in feet

$W_E$  = Weight of Explosive in pounds

$W_F$  = Weight of Fish in pounds

DOB = Depth of Burst in feet

# REPORT DOCUMENTATION PAGE

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